Design Simulation and Analysis of Polysilicon-based CMOS Micromachined Piezoresistive Microcantilever for Glucose Sensing

Nina Korlina Madzhi, Anuar Ahmad

***Abstract*- The measurement of glucose is of great importance in clinical diagnosis. This is especially essential for the continuous monitoring for example in a patient suffering from diabetes mellitus which is caused by the high levels of glucose in human physiological fluid. Even though many research have been done for glucose measurement, there are still many research in progress to develop new methods and technologies for sampling, detecting and monitoring glucose levels. This work has focused on the design simulation analysis of a Polysilicon-based CMOS micromachined Piezoresistive Microcantilever beam for glucose sensing application. In principle, adsorption of glucose on a functionalized surface of the microfabricated cantilever will cause a surface stress and consequently the cantilever bending. In this paper, the microcantilever beam is constructed and bending analysis is performed so that the beam tip deflection could be predicted. The device model was simulated using CoventorWare^{TM}, a commercial finite element analysis (FEA) tool designed specifically for MEMS applications. The structural variation of the piezoresistors designs on cantilever beam is also considered to increase the sensitivity of the microcantilevers sensor since the forces involved is very small.**

***Keywords*-Piezoresistive, Microcantilever, Glucose, MEMS, CMOS**

I.INTRODUCTION

Over the past decade there is a dramatic increase in sensor research and developments and applications. There are tremendous advances made in sensor technology and the sensing technologies developed are as varied as the applications such as from materials to micro and nano sensors to wireless networks. Sensor design and operation requires a cross-disciplinary background likes electrical engineering, mechanical engineering, physics, chemistry, biology, industrial, etc. MEMS Biosensor (Bio-MEMS) devices are used in detecting infectious diseases such as HIV, DNA analysis, proteins and genotypes. They have established markets and finding new applications, leveraging on a combination of low manufacturing costs, compact size, low weight and power consumption as well as increased multi-functionality.

A series of market analysis reports on Bio-MEMS is issued by Francisco et al. which stated that a market of 3 billion dollars for bio-chips was foretold for 2004 which include a growth of 800% for DNA chips, 1000% for Protein chips, 1000% and 60% bilirubin analyzers 60% for new born[1].

A. Piezoresitive Microcantilever

Cantilever sensors are based on relatively well known and simple transduction principle “A simple cantilever beam can be used as a sensor for biomedical, chemical and environmental application[2]”. Fig.1 shows a target biochemical species adsorbing on a functionalized surface of the cantilever beam.

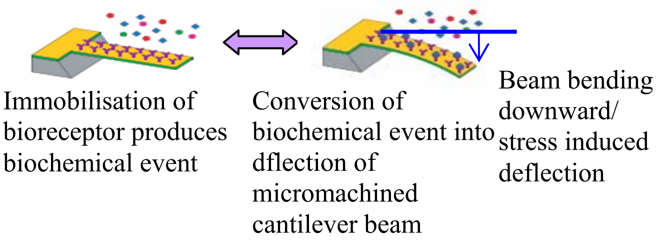

Fig. 1 The microcantilever beam response

The changes in the surface properties of the microcantilever through absorption or adsorption of analytes to receptor molecules will influence its surface stress. This causes the deflection of microcantilever and it is proportional to the analyte concentration[3]. Usually the deflection is in micrometers and can be detected by several method such as optical[4]and capacitive detection[5].There is increasing concern that the requirement for external devices for deflection measurements such as lasers, optical fibers or capacitors is the disadvantages of these techniques where the alignment and calibration of these external elements are required.

However, by integrating piezoresistive material, the disadvantages can be avoided where Piezoresistive microcantilevers can detect the changes in surface stress due to cantilever deflection upon adsorption or absorption. This paper uses finite element analysis to simulate the geometrical parameters for polysilicon-based piezoresistive microcantilevers by using Coventorware. The displacements and the $\Delta R/R$ changes of the cantilevers were also discussed.

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II. DESIGN SIMULATION

In this section, the simple piezoresistive microcantilever design use in simulation is shown in Fig. 2.1

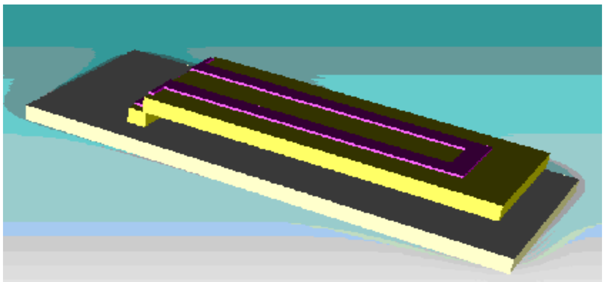

Fig.2.1 A solid 3-D model of piezoresistive microcantilever

Fig.2.2 shows the schematic for a microcantilever beam subjected to a concentrated moment on its free and while the other end is fully constrained.

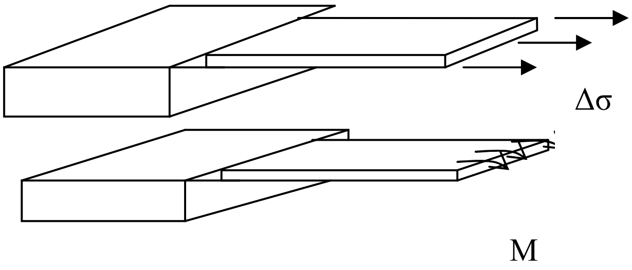

Fig 2.2 Fixed- free end Microcantilever beam

Based on the Stoney equation assumption, the surface stress bends the microcantilever beam with uniform curvature into the concentrated moment induced bending and the following curvature relation is given by [6]:

$$k = \frac{M_0}{EI} \qquad (2.1)$$

Where M_0 is the applied concentrated moment, E is the elastic modulus and I is the moment of inertia of the beam. By comparing with the curvature relations, the following relation between the surface stress and the moment per unit length can be established as

$$M_0 = \frac{\Delta\sigma t}{2} \qquad (2.2)$$

Since the moment is directly proportional to the induced surface stress and the microcantilever beam geometry property, the above can be further simplified as

$$z = \frac{2(1-\upsilon)\Delta\sigma}{E}\left(\frac{l}{t}\right) \qquad (2.3)$$

Which is a well known form of Stoney equation commonly used to measure the deflection caused by residual surface stresses in thin films [6]. $\Delta\sigma_s$ is the differential surface stresses on the surface of the microcantilever, *E* the is the Young's modulus, *v* is the Poisson's ration, r and h are the radius of curvature and thickness of microcantilever beam. For piezoresistive microcantilever in Fig. 2, the relationship between the surface stress and the relative change in resistance $\Delta R/R$ for a piezoresistor is given by[7];

$$\frac{\Delta R}{R} = -K\left(\frac{1}{E_1h_1+E_2h_2} + \frac{Z_T^2}{E_1h_1\left(\left(Z_T-(h_1+h_2)+\frac{h_1}{2}\right)^2+\frac{1}{3}\left(\frac{h_1}{2}\right)^2\right)+E_2h_2\left(\left(Z_T-(h_1+h_2)+\frac{h_2}{2}\right)^2\right)}\right) \quad (2)$$

$$x\Delta\sigma_s$$

(2.4)

where E_1, h_1, are the Young's modulus and thickness of the polysilicon cantilever beam while E_2, h_2, Young's modulus and thickness of the piezoresistor, Z_T is the distance from neutral axis to top of the cantilever beam containing piezoresistor and K is the gauge factor of piezoresistor but only applies when the length of the Si piezorresistor is the same as the cantilever length.

III SIMULATION RESULTS AND DISCUSSION

A solid 3-D model (Fig. 2.1) was created based on the thin film material property data. The finite element technique was used to solve the differential equations of each physical domain where the differential equations are solved by discretizing the 3-D model into a mesh that consists of a number of elements with a specified number of nodes. After the mesh model is generated MemMech solver was used to analyze the variable stress simulation (Fig.3) with the same conditions of analyzes concentration and the same analyze capturing area.

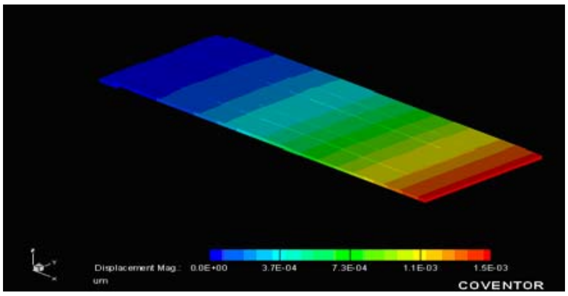

Fig. 3 Active area with applied stress from 2 to 10 Pa of initial state

A. Effects of Microcantilever Beam Thickness on Piezoresistive Microcantilever Deflection

Polysilicon material is used as the piezoresistor in this piezoresistive microcantilever design simulation. The Polysilicon material properties used in this work are as shown in TABLE 3 below.

There are four piezoresistive microcantilever designed named as PZR10, PZR20, PZR30 and PZR40 respectively as shown in Fig. 3.1.

The length and width of microcantilever beam design used in the simulation is fixed at 195µm x 70µm. However, the difference between these four designs is the thickness of the BPSG sacrificial layer: 0.9µm and 1.8µm; and the length of the piezoresistor which is at 80µm, 110µm, 140µm and 170µm.

TABLE.3
POLYSILICON MATERIALPROPERTIES

Material	Polysilicon
Elastic Constants	E(MPa):1.69e+005, Poisson:2.2e-001
Density(kg/µm^3)	2.32e-015
TCE Integral Form(1/K)	2.8e-006
Thermal Cond(pW/µmK)	1.48e+008
Specific Heat(pJ/kgK)	7.12e+014
Dielectric	0e+000
PiezoResistiveCoeffs(1/MPa)	Pi_11: 1e-009 Pi_12:1e-011 Pi_44:1e-004
Tensile strength	1.2 GPa

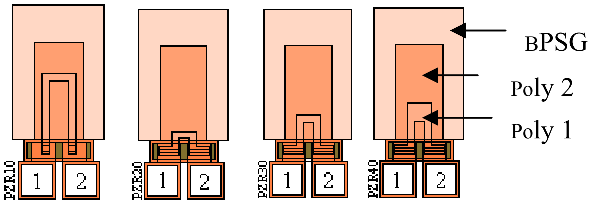

Fig. 3.1 Piezoresistive (PZR) microcantilever design structure

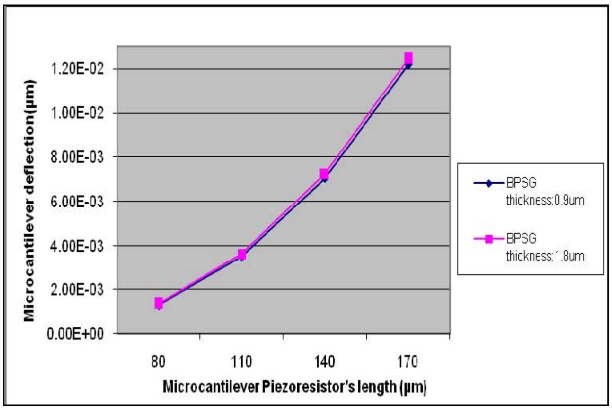

Fig.3.2 The microcantilever beam with 0.5µm thickness deflection for four different piezoresistor lengths and two different sacrificial layer thickness when a 2 N/m (Pa) surface stress is applied on the surface.

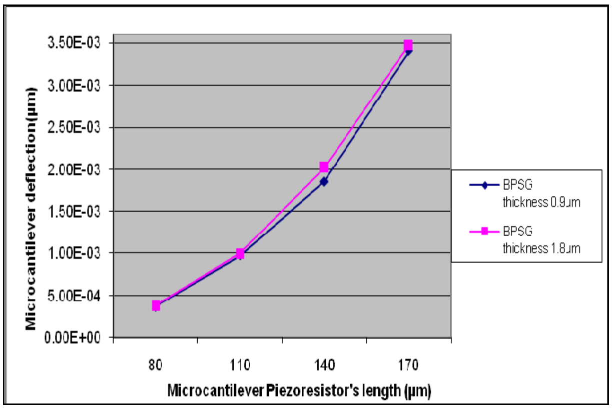

Fig.3.3 The deflection displacement of a PZR microcantilever beam with 1.0µm thickness versus the piezoresistor length when a 2 N/m surface stress is applied on the surface.

Surface stress of 2 N/m were selected as the minimum value in this study because the surface stress changes at this level have been observed in many microcantilever chemical/biosensors. From Fig.3.2 and Fig.3.3 above, it can be observed that, when a 2 Pascal force applied onto the microcantilever, the microcantilever deflection is higher for the 0.5µm thick microcantilever compare to the 1.0µm thick microcantilever. By comparing within the BPSG sacrificial layer, the BPSG sacrificial layer with the least thickness produces the higher deflection value. For both microcantilever thickness, as the piezoresistor's length increases the deflection is also increases.

B. *Effects of Sacrifical Layer (BPSG) Thickness on Piezoresistive Microcantilever Deflection.*

Two designed piezoresistive microcantilever simulation models with each sacrifical layer made from Boronphosphosilicate Glass (BPSG) material have thickness of 0.9µm and 1.8µm. In this simulation, a 2 Pascal (Pa) force applied to microcantilevers with four different piezoresistor's length and two microcantilever thickness of 0.5µm and 1.0 µm.

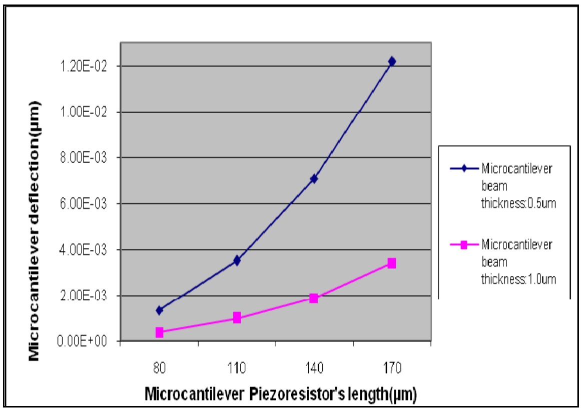

Fig.3.4 Piezoresistive microcantilever deflection when a 2 Pascal force applied to the microcantilever with sacrificial layer thickness of 0.9µm with two different microcantilever beam thickness of 0.5 µm and 1.0 µm

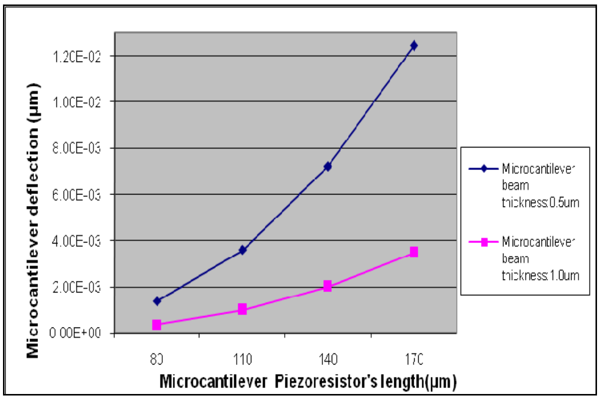

Fig.3.5 Piezoresistive microcantilever deflection when a 2 Pascal force applied to the microcantilever with sacrificial layer thickness of 1.8µm with two different microcantilever beam thickness of 0.5 µm and 1.0 µm

The designed microcantilever size is 75µm in width. The deflections of four different length of PZR microcantilevers (80µm, 110µm, 140µm and 170µm) when a 2 N/m surface stress is applied on the surface of each piezoresistor is shown above for BPSG sacrifical layer thickness of 0.9µm (Fig3.4.) and 1.8µm (Fig.3.5). In Fig.3.4, when the piezoresistive microcantilever with BPSG sacrificial layer of 0.9µm thickness, the microcantilever beam with 0.5µm thickness shows the largest microcantilever beam deflection when compared to the microcantilever beam with 1.0µm thickness. Fig.3.5 with BPSG sacrificial layer of 1.8µm thickness, the microcantilever beam with 0.5µm thickness also shows the larger deflection when compared to the microcantilever beam with 1.0 µm thickness. However, the different in these two graphs is that BPSG sacrificial layer with the least thickness at 0.9 µm have the largest deflection at approximately 0.013 µm for piezoresistor length at 170 µm for microcantilever beam thickness at 0.5 µm . For BPSG sacrifical layer of 1.8 µm, the maximum deflection is at 0.00348 µm when the piezoresistor length is 140 µm.

C. *Design Stress Simulation of Piezoresistive Microcantilever*

Other than microcantilever deflection obtained, the FEA stress results also use Von Mises Stress to measure the yielding occurs when the design stress exceeds the material yield strength. Design stress is the maximum surface under simple loading conditions or Von Mises stress in complex loading conditions.

Fig.3.6 shows the misses stress obtain from simulation when force applied onto piezoresistive microcantilever and it can be observed that the measured mises stress does not exceed the the polysilicon tensile strength of 1200 MPa because if the mises stress is greater than the tensile strength, the material will theoretically break[8].

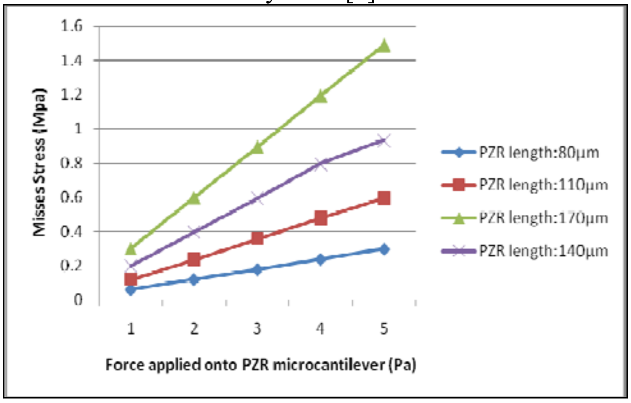

Fig.3.6 Mises Stress of PZR microcantilever with different applied force

D. Piezoresistive Microcantilever Fabrication Process

The fabrication of the piezoresistive microcantilever was performed at MIMOS semiconductor (MySEM). It uses CMOS surface micromachining method since the structures involved several layers and so that the microcantilever beam can be "released" to allow it to move vertically. Besides being the common surface micromachining structural material, Polysilicon material could also be deposited with well-controlled and repeatable film stress level. The fabrication is based on four basic microfabrication techniques: deposition, patterning, doping and etching.

The fabrication process started from patterning a 0.9µm – thick photoresist of BoronPhosphosilicateGlass (BPSG) sacrificial layer on a silicon substrate by standard photolithography. The microcantilever beam is then formed by depositing a polysilicon layer of 5000A (0.5Qm) thickness using Low Pressure Chemical Vapor Deposition (LPCVD).Next, a 500nm-thick Silicon Nitride (SiN) layer is deposited by Plasma Enhanced Chemical Vapor Deposition (PECVD) which will act as an insulator. Another polysilicon layer is then deposited with a dimension of 195µm x 75 µm u-shape resistor pattern and blanket implanted to achieve a resistor value of 1.2kΩ.. Then the electrode pad was patterned and deposited with Aluminium and finally the cantilever beam is released by wet etching. The cross section SEM image of the designed piezoresistive microcantilever is as shown in Fig.3.7.

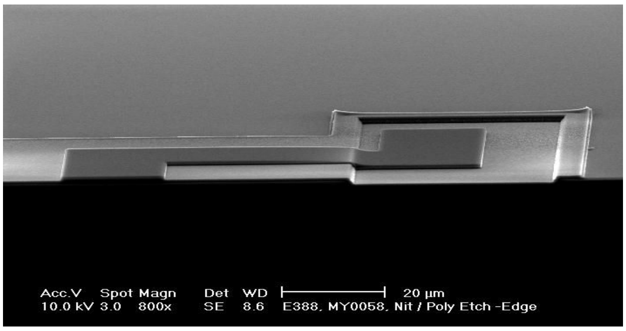

Fig.3.7 FESEM of microcantilever sensor cross section

IV. CONCLUSIONS

The finite element modeling was used to simulate the mechanical behaviour of a MEMS cantilever with the possibility of detecting the glucose concentration. The read out signal can been done by piezoresistive sensing with the polysilicon resistors arranged in a Wheatstone bridge configuration where the output voltage of the bridge is directly proportional to the amount of cantilever deflection.

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